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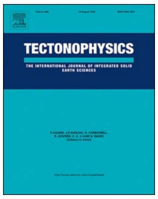

Reconstruction of early phase deformations by integrated magnetic and mesotectonic data evaluation

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ABSTRACT

Markers of brittle faulting are widely used for recovering past deformation phases. Rocks often have oriented magnetic fabrics, which can be interpreted as connected to ductile deformation before cementation of the sediment. This paper reports a novel statistical procedure for simultaneous evaluation of AMS (Anisotropy of Magnetic Susceptibility) and fault-slip data. The new method analyzes the AMS data, without linearization techniques, so that weak AMS lineation and rotational AMS can be assessed that are beyond the scope of classical methods. This idea is extended to the evaluation of fault-slip data. While the traditional assumptions of stress inversion are not rejected, the method recovers the stress field via statistical hypothesis testing. In addition it provides statistical information needed for the combined evaluation of the AMS and the mesotectonic (0.1 to 10 m) data. In the combined evaluation a statistical test is carried out that helps to decide if the AMS lineation and the mesotectonic markers (in case of repeated deformation of the oldest set of markers) were formed in the same or different deformation phases. If this condition is met, the combined evaluation can improve the precision of the reconstruction. When the two data sets do not have a common solution for the direction of the extension, the deformational origin of the AMS is questionable. In this case the orientation of the stress field responsible for the AMS lineation might be different from that which caused the brittle deformation. Although most of the examples demonstrate the reconstruction of weak deformations in sediments, the new method is readily applicable to investigate the ductile-brittle transition of any rock formation as long as AMS and fault-slip data are available.

1. Introduction

Reconstruction of the former orientations of past deformations of geological units is one of the key questions in the geosciences. In several cases the small amount of overall deformation is reflected in only a few, weak markers making historical analysis difficult, often impossible. The ductile to brittle sequence of deformation styles is widely presumed during the deformation history for most rocks (lithifying sediments, cooling magmatic and some metamorphic rocks). If the basic cause of the deformation – namely stress – prevails beyond the early (ductile) phase of deformation, then it might lead to brittle fracture (faults, joints, deformation bands) in the rock unit (Talbot, 2008). Our work aims to approach this transition, in particular cases, when it takes place in a predominantly steady stress field. An integrated method that facilitates two, frequently available indicators, and exploits relatively low range of deformation, might shed light on the transitional field of the ductile and brittle deformation styles.

Both magnetic fabric (AMS, Anisotropy of Magnetic Susceptibility) and mesotectonic markers are widely used for reconstructing past deformation phases (following Turner and Weiss (1963) and Hancock (1985), the mesotectonic scale refers to the range between 0.1 m and 10 m). Although later deformation phases may occur, this transition phase is unique as it is the only one that is reflected by both quasi-simultaneous magnetic and mesotectonic markers. In the terms of continuum mechanics, we thus consider the first increment of the strain.

In both AMS and fault-slip methods there are doubts about whether the directions of the stress field are reflected more precisely in AMS or in brittle deformations. Some studies (e.g. Haernick et al., 2013) point out that AMS is an unreliable predictor of not only stress, but even strain. Others simulate well-defined multiphysical models and demonstrate the highly nonlinear dependence of the susceptibility tensor on the finite strain during successive events of deformations (Ježek and

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Hrouda, 2002). Undoubtedly, such observations and models must be valid for the general situation in which any material under any specific deformation is distorted to an arbitrary extent. However, in the case of weak deformation of homogeneous sediments, a correlation has been demonstrated between stress (reflected by brittle deformation markers) and AMS data ((Borradaile and Hamilton, 2004; Cifelli et al., 2005; Ferré et al., 2014) and references therein). These studies, in principle, state that the formation of the AMS fabric takes place during the early, unconsolidated stage.

The intuitive physical picture outlined above relies on the following assumptions:

- the AMS reflects the weak deformation of the early, ductile phase, prior to advanced lithification;
- the cause of the deformation lasted sufficiently to produce brittle markers;
- in sedimentary rocks, the deformation happened while the layers were horizontal.

Unfortunately, even if the above criteria are met, statistical analysis is difficult because we are dealing with weak deformations and both AMS and mesotectonic markers are sparse. So the available data tend to be noisy, making statistical treatment of such data-sets uncertain. In the case of tensor quantities some linearization technique can usually be applied to statistically evaluate eigendirections of the tensor (e.g. Cai and Grafarend, 2007). If the eigendirections are considered as independent vectors, then procedures developed for vectors can be used, such as Fisher statistics over the sphere (Fisher et al., 1993), or its modified version by Bingham (1974) or Henry and Le Goff (1995). Random sampling with replacement known as "bootstrapping" might help to overcome the difficulties of small sample size or unknown distribution type (Tauxe et al., 1990, 1991). Several authors point out that these approaches completely neglect the tensor nature of the observed quantities (Constable and Tauxe, 1990). Methods, which aim to keep consistency with the underlying physics strongly rely on linearization techniques (Hext, 1963; Jelinek, 1978), but as pointed out in Hext (1963), the error due to the linearization (i.e. neglecting higher order terms in the Taylor series of a tensor) can be quite large, hence the approximation of the confidence intervals might be poor. It is not difficult to see that two, sufficiently close eigenvalues of the tensor (which situation is referred to as *rotational anisotropy* throughout the paper) lead to the underestimation of the confidence regions by any method built on linearization.

In this paper a statistical framework for tensor quantities is presented that – apart from a mild assumption about normal distribution of the input data – is free from other *a-priori* assumptions (i.e. it is able to handle data-sets represented by closely rotationally anisotropic tensors), and the accuracy of the computed confidence intervals does not depend on intrinsic characteristics of the outcome (such as the degree of AMS lineation).

Our approach is readily applicable for AMS data sets and can be extended to the stress inversion applied in mesotectonics. The idea of using both sources simultaneously in reconstructing the orientation of past stress field is common practice and relies heavily on visual comparison of stereograms and hence biased by human intuition. The new method of combined statistical evaluation of the AMS and mesotectonic data can be applied to several kinds of geological objects. It can be used to study the ductile to brittle transition and investigate the steadiness of the stress field. However, it is particularly powerful when the maximum and intermediate axes of the AMS ellipsoid are of similar length, as in moderately deformed samples of soft and fine grained sediments, and where the availability of the mesotectonic data is limited.

Although this paper is devoted to the statistical procedure itself, the methods to obtain AMS and mesotectonic data will also be discussed briefly and the applicability of the method will be demonstrated using field examples from the Pannonian basin, Central Europe.

1.1. *AMS measurements and the interpretation of the results in terms of deformation*

The AMS ellipsoid is determined on oriented field samples. The magnetic susceptibility tensor for each sample is measured on different instruments (Studýnka et al., 2014). During the measurement the sample is placed in a magnetic field (**H**) and its magnetization (**M**) is determined for several spatial orientations. The magnetic susceptibility tensor describes the linear transformation between the vectors **H** and **M** via $\mathbf{M} = \mathbf{kH}$. It can be represented by a 3 × 3, symmetric, real valued matrix,

$$\mathbf{k} = \begin{bmatrix} k_{11} & k_{12} & k_{13} \\ k_{12} & k_{22} & k_{23} \\ k_{13} & k_{23} & k_{33} \end{bmatrix}. \tag{1}$$

Several devices and testing procedures are available to carry out the measurements, details for which are provided by Jelinek (1988) and Studýnka et al. (2014), and references therein. The AMS ellipsoid characterizes the magnetic fabric of a rock. It is considered as *primary* in a sediment formed during deposition and, in igneous rocks, during cooling in the absence of external forces. In sediments, the AMS ellipsoid is oblate, the orientation of the maximal principal axis (denoted as K1) extends over a wide range of azimuths, sometimes even in a single layer, but always throughout a stratigraphic sequence, due to the temporal changes of the flow direction within the sedimentary basin. In some cases a general trend can be observed that is maintained throughout a stratigraphic sequence, especially in the fine grained clastics (mudstones). This trend can be attributed to *weak tectonic deformation* (Mattei et al., 1997; Cifelli et al., 2005; Márton et al., 2006; Márton et al., 2009, 2012), especially when K3 is close to the bedding pole, i.e. the magnetic foliation is subparallel with the bedding plane. The deformation leaving a magnetic imprint in these sediments is primary, the first one after the deposition. Overprinting of this early AMS fabric by subsequent tectonic phases is unlikely, as the magnetic fabric of the sediment more readily reflects strain while the sediment is relatively soft, i.e., able to undergo continuous (ductile) deformation and did not go through cementation process (Borradaile, 1988). The magnetic fabrics of igneous (lava) rocks can be affected by strain while they are not yet completely cooled (Márton et al., 2006; Lesić et al., 2013). Afterward which their fabrics are difficult to modify (Tarling and Hrouda, 1993).

1.2. *Methodology of fault-slip analysis*

Field measurements generally comprise the measurement of strike and dip data of striated fault planes, joints, deformation bands or other types of brittle elements. Fault kinematics can be determined using divers criteria described in several papers (Angelier, 1979; Hancock, 1985; Petit, 1987). Starting from fault-slip data several algorithms were elaborated for calculation of the $\boldsymbol{\sigma}$ stress tensor (Angelier, 1984, 1990; Žalohar and Vrabec, 2007, 2008). In most cases only the reduced stress tensor is determined incorporating the orientation of stress axes and their ratio, but not their absolute value (Carey and Brunier, 1974).

In the case of multiple faulting phases, a combination of automatic (Angelier and Manoussis, 1980) and manual separation, or their combination, can be used to separate faults into phases. Some of the data in this paper were analyzed in a combined way (Sipos-Benkő et al., 2014; Fodor et al., 2014). The tilt test is useful and important for sedimentary rocks in order to establish the relative chronology between faulting and tilting around a horizontal axis. For a conjugate set of faults, that underwent tilting, the symmetry plane of faults and also the stress axes deviate from vertical and horizontal; thus backtilting of faults to their horizontal bed position would reconstruct the original position of the stress axes at the time of faulting. Although the tilting itself and the faulting could belong to the same deformation phase, these successive